DISTRIBUTED BEAM FORMER FOR DISTRIBUTED-APERTURE ELECTRONICALLY STEERED ANTENNAS

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ABSTRACT

Applications for electronically steered arrays (ESA) in army communication systems span frequencies from UHF to Ka bands and requirements that include single and multiple beams, various scanning speeds, and different polarizations. The radiating apertures can be planar, conformal or segmented and distributed over multi-faceted structures. Examples include distributed apertures on military vehicles, antennas on elevated posts or towers on stationary or mobile platforms, and others. The beam former is an essential part of the ESA design and its optimization in functionality and cost lead to improving the whole system. This paper presents a concept for a distributed beam former that is composed of two stages: an RF stage with limited scanning steps and a digital stage that is capable of steering multiple beams in all required directions. The two-stage beam former uses fewer A/D converters than its all-digital counterpart and lower losses than the all-RF beam former. Examples are given for multi-faceted apertures.

1. INTRODUCTION

There are several applications for phased arrays in army communication systems. This spans frequency bands ranging from UHF to Ka bands and performance requirements that include single and multiple beams, various scanning speeds, and different polarizations. The radiating apertures can be planar, conformal or segmented and distributed over multi-faceted structures. Examples include distributed apertures on HMMWV platform, conformal aperture on UAV aircraft body, antenna on elevated post or tower on a stationary or mobile platform, and others. This arrangement has the advantage of providing higher gain and thus lower power relative to the omni-directional antenna that is often used.

Such use of multifaceted and conformal electronically scanned antennas on army vehicles has been depicted in (Kilic and Weiss, 2006) for conformal arrays, and in (Kilic and Zaghloul, 2002; Zaghloul and Kilic, 2003) for multifaceted array for vehicle-to-vehicle communications. Mechanical scanning has also been used for army vehicle Satellite-on-the-Move (SOTM) and Satellite-on-the-Pause (SOTP) systems (Kilic et al, 2001) with limited capabilities in scanning speeds and single beam operations.

The beam former is an essential part of the phased array design. The complexity of beam forming is a function of the number of elements in the array, scanning steps, scanning range, and the number of beams in a multibeam system. Typically two different beam forming types are used in these systems: RF and digital. Both have different limitations that depend on the mechanism of forming the beams. Multibeam RF beam formers can be implemented using phase-shifter-populated beam forming matrices. The smallest phase shift determines the scanning steps for RF beam formers, and the number of required phase shifters depends on the number of array elements and the number of simultaneous beams. This results in a high-loss, high-cost beam former design. The loss and cost increase as the number of scanning steps increase for RF beam formers. Digital beam formers employ A/D converters followed by a processor, where the number of the scanning steps is not a major factor in the beam former complexity. However, digital beam formers typically require as many A/D converters as the number of array elements. The challenge is to design a low loss beam former, which uses a small number of components yet does not sacrifice performance.

2. DISTRIBUTED BEAM FORMING CONCEPT

A low-cost, low-loss and light weight beam former for distributed or conformal aperture antenna is presented here. The array is divided into modular sub-arrays, and its beam former is distributed in two stages. The first stage is at the sub-array level with a small number of pre-set scanning positions that are realizable using a Butler matrix, printed Rotman lens or other switched time delay system. This stage ends with the multiplexed multibeam signals fed into a single A/D converter per sub-array. The second stage is a central digital beam former that operates on the combined outputs of the sub-arrays.

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Whether the array is of planar or conformal aperture, it will be replaced by a distributed aperture configuration with a base-band digital network that is used to combine signals from the distributed apertures. The concept is shown in Figure 1 for receive mode of operation. The signal received by each sub-array is downconverted, A/D converted and combined with other sub-arrays' signals via a base-band cable. A digital signal processor will perform phase compensation when combining the signals from the different subarrays. This will allow for the correction for the path loss and LNA differences for each subarray. The figure shows the two beam forming stages. In the first stage, the outputs of the radiating elements of the subarray are fed to a LNA and are demultiplexed to the individual channels of the different beams. Each sub-array module uses a multibeam beam forming matrix or a single-beam beam forming network that can be designed with pre-set scanning directions. The beam former for this stage can be realized using a printed Butler matrix (Bona et al, 2002; Neron and Delisle, 2005), a printed Rotman lens (Kilic and Dahlstrom, 2005) or other switched time delay system. The absence of variable phase shifters or variable delay lines with associated high-loss switches reduces the losses incurred by the sub-array beam former. The outputs of the different beams are multiplexed after the first stage to allow for using a single down-converter and a single A/D converter per sub-array. In the second stage, the A/D converter outputs are combined and then digitally demultiplexed. A single A/D per sub-array versus one per array element presents a significant saving, which results in reduced power consumption, number of components and cost.

In the transmit mode of operation, the reverse process is employed, where a common processor will transmit the phased signals to the sub-arrays. The signals received by the sub-arrays will go through the pre-set beam forming and are retransmitted such that the signals are combined in space to form the desired beam.

The pre-set scanning directions of the sub-arrays depend on the orientation of the sub-array in the conformal structure. At the digital beam former stage, the phases imposed per sub-array are determined based on an optimization process that takes into account the scanning directions of the sub-arrays, which are in turn selected based on the required scanning steps and overall scanning range of the whole array.

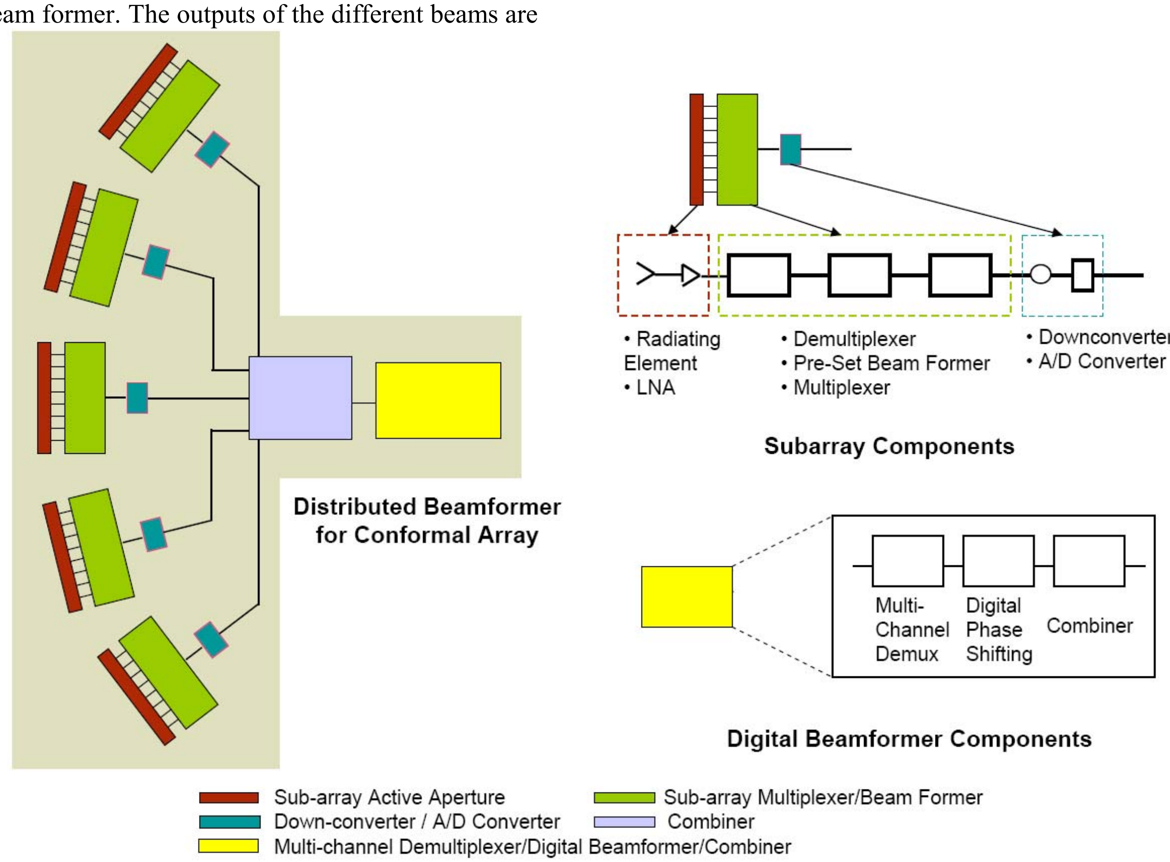

Figure 1. Distributed Beam Former Concept

3. FIRST STAGE OF DISTRIBURED BEAM FORMER

The first stage in the distributed beam former uses a RF beam former that has pre-set scanning directions. In a conformal array or a large planar array that is divided into sub-arrays, the pre-set scanning directions may be different for different sub-arrays. In addition, each beam former can support multiple beams. A switch matrix controls the pre-set scanning directions for the different beams according to the sub-array location in the whole array and according to the desired beam scanning direction of the whole array. Two of the possible realizations of the first stage beam former are the Butler matrix and the Rotman lens.

Butler Matrix Realization:

Butler matrix is a passive device for the realization of pre-set phase front with equal phase differences among the output ports. This is achieved through a multi-stage circuit configuration that uses a symmetric arrangement of hybrids and phase shifters. Figure 2 shows an example of an 8 X 8 Butler matrix. The number of inputs is equal to the number of outputs and is a binary number of 2^n. The 2^n X 2^n matrix uses $2^{n-1} \log_2 2^n$ hybrids and a number of phase shifters that are functions of the required phase fronts at the array ports of the matrix (Denidni and Libar, 2003). The phase shifters are usually realized as passive delay lines. For multiple beams or for a switchable phase fronts for different beam direction, a switch or a switch matrix is inserted at the beam ports of the matrix. While the numbers of input and output ports of the matrix are equal, the number of usable beam ports may be far less. The binary and equal numbers of the matrix input and output ports may pose a limitation on using it, and the number of hybrids may be excessive if the number of ports is large.

Realizations of Butler matrix in printed circuit medium has been reported in recent years. Bona et al (2002) built a low-loss compact Butler matrix using the two sided structure of suspended striplines. The use of the two sides facilitates the realization of the transmission line crossings that are inherent in the matrix configuration. Neron and Delisle (2005) showed a similar implementation using a bi-layer microstrip structure that utilizes a slot layer to couple between the two printed layers.

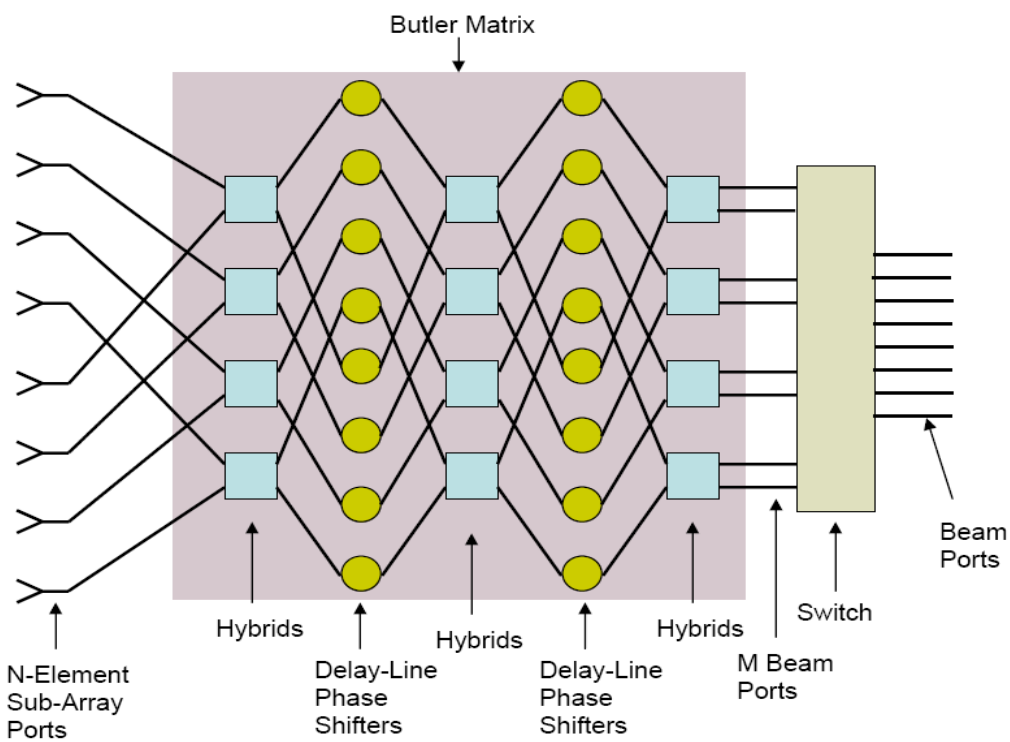

Figure 2. First Stage of Distributed Beam Former: Butler Matrix Option

Rotman Lens Realization:

The realization of the pre-set beam former using Rotman lens alleviates some of the inherent problems associated with Butler matrix. The lens also has the advantage of operating over wide bandwidths. However, its design and optimization can be more involved. Figure 3 shows the basic components of a Rotman lens (Djordjević et al, 2004). The numbers of input and output ports are subject to geometric rather than configuration restrictions. The lens elements on the beam side correspond to scanning directions and each element illuminates the array side with a certain taper to produce the desired phase front. This puts restrictions on the element sizes that may restrict the number of pre-set scanning directions. As is in the Butler matrix option, a switch matrix controls the location of the pre-set beams for the sub-array to satisfy the scanning requirements of the whole array.

Several realizations of the Rotman lens in printed circuit media have been reported. Of significance is the development by the Army of a number of Rotman lenses and the on-going programs to investigate the use of Rotman lens for future Army applications (Kilic and Dahlstrom, 2005).

Although the description of the Butler matrix and Rotman lens above addressed linear or piece-wise linear configurations for one dimensional scanning, two dimensional scanning can also be realized using the two designs. The choice of the proper design depends on the overall scanning requirements of the complete array.

4. SECOND STAGE OF DISTRIBURED BEAM FORMER

The second stage of the distributed beam former is a digital beam former that operates on all the beams simultaneously. To reduce the number of A/D converters, the beam outputs, shown in Figures 2 and 3, that use different channels are multiplexed in the frequency domain and the aggregate sum is downconverted and converted to a digital signal using a single A/D converter per sub-array. Digital cables connect the A/D outputs at the sub-arrays to the central digital processor for the whole array. The multi-channel input is demultiplexed and digital phase shifting is applied to individual channels to produce the right phase front for each channel. The digital phase shifters can operate with high resolutions and can compensate for errors that accumulate in the signal paths. The outputs of the individual digital beam formers are multiplexed in the time domain and then sent to the common receiver, or sent as individual channels to separate receivers.

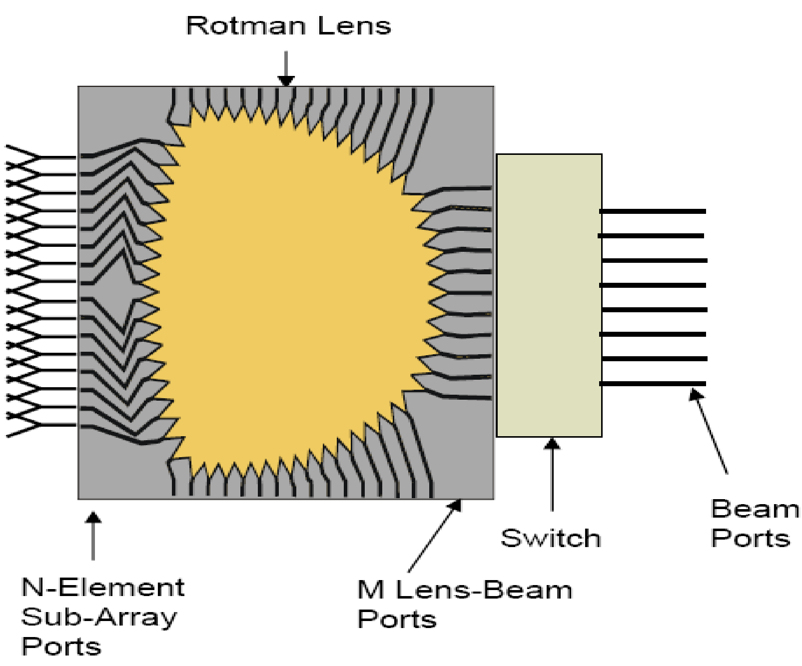

Figure 3. First Stage of Distributed Beam Former: Rotman Lens Option

5. COMPARISON WITH SINGLE-STAGE BEAM FORMERS

To show the advantages of distributing the beam forming process into two stages, Table 1 presents a qualitative comparison between the single-stage RF beam former, single-stage digital beam former and the distributed beam former with RF and digital beam forming stages. The advantages are primarily in the reduction in the number of the A/D converters as compared to the full digital beam former and in the reduction in the lossy variable phase shifters in the RF beam formers. The comparison with the RF beam former assumes the full flexibility in the beam scanning directions, hence the need for a variable phase shifter per beam per radiating element. Butler matrices or Rotman lenses can also be used for a full RF beam former at the expense of the scanning steps. It also may cause more complex structure for conformal or multi-faceted arrays.

A simple quantitative comparison is shown in Table 2. In this example we assume a 20-element array divided into five sub-arrays with four elements each. The number of pre-set beam directions in the first stage is thus limited to four. The comparison shows the advantages of the distributed beam former using Butler matrix in the first stage over the full single-stage beam former using variable RF phase shifters, Butler matrix and digital beam former. It should be noted that the use of the Rotman lens, instead of the Butler matrix may have advantages in the component count, but may be limiting in the scanning steps. As mentioned, although this example is for a linear or piece-wise linear, one dimensional scanning, similar examples can be devised for three-dimensional array with two dimensional scanning.

Table 1: Comparison between RF, Digital and Distributed Beam Formers for N elements and M beams

Beam Former Type	RF Losses	Signal Distribution Cabling	# of Variable Phase Shifters	# of A/D Converters	Complexity of RF Beam Forming Stage	Cost
RF Beam Former	High	RF	M X N	0	High	High
Digital Beam Former	Low	Digital	0	N	n/a	Medium/High
Distributed Beam Former with K Subarrays	Low	Short RF, Long digital	0	K (<< N)	Low	Low

Table 2: Comparison between RF, Digital and Distributed Beam Formers for 20 Elements and up to 4 Beams

Beam Former Type	# of Variable Phase Shifters	# of Hybrids	# of A/D Converters
RF Beam Former with Phase Shifters	80	0	0
RF Beam Former with Butler Matrix	0	80	0
Digital Beam Former	0	0	20
Distributed Beam Former with 5 Sub-arrays Using Phase Shifters	80	0	5
Distributed Beam Former with 5 Sub-arrays Using Butler Matrices	0	20	5

6. ILLUSTRATIVE EXAMPLE

To illustrate the concept of distributed beam forming, scanning and beam forming performance of a 5-sub-array conformal array was simulated. The 5 sub-arrays were oriented in the directions 0, ± 15 and ± 30 degrees from the full array broadside direction and contains 4 elements each. The pre-set scanning directions in each of the sub-arrays were set at increments of 15 degrees. The theoretical pre-set phase shifts for the 15-degree increments are shown in Table 3. A practical realization of the first-stage beam formers may require adjusting or quantizing these phase shift values. The digital beam former stage allowed the overall scanning to be at finer scanning steps. The phases per a sub-array added at the digital beam former are function of the locations of the sub-arrays relative to each other. In this example, the sub-array centers are placed on a conformal curve that is not a straight line. The corresponding second stage phase shifts for different scanning angles are tabulated in Table 4. The aggregate phase shifts to produce beams at certain scanning angle are the sums of the phase at the two stages. Table 5 shows the scanning directions set by each of the two stages in order to produce conformal array beams at 5-degree increments from broadside to 35 degrees. The beam patterns at the scanning increments of 5 degrees are shown in Figure 4. Other directions can be added by optimizing the phase values in the digital beam former. It should be noted that this example dealt with a one-dimensional array conforming to a curve, in which scan loss is not a major issue. This is apparent in the patterns that resulted from the analysis. In a planar array, scan losses will limit the scanning range of the antenna. In addition, although this example illustrates the concept for one-dimensional scanning, two-dimensional operation can also be implemented and scan loss will be a factor in the design. Another factor is the size of the sub-array. Small sub-array sizes will produce broader sub-array beams, allowing for fewer pre-set scanning steps in the first stage.

Table 3: First Stage Beam Former Phases for the Sub-Array Elements for 5 Pre-Set Scanning Angles

Scanning Angle, deg.	Phase of Element 1, deg.	Phase of Element 2, deg.	Phase of Element 3, deg.	Phase of Element 4, deg.
0	0	0	0	0
15	69.88	23.29	-23.29	-69.88
30	135	45	-45	-135
45	-169.08	63.64	-63.64	169.08
60	-126.17	77.94	-77.94	126.17

Table 4: Second Stage Beam Former Phases for the Sub-Arrays for Dynamically Controlled Scanning Directions

Scanning Angle, deg.	Phase of Sub-Array 1, deg.	Phase of Sub-Array 1, deg.	Phase of Sub-Array 1, deg.	Phase of Sub-Array 1, deg.	Phase of Sub-Array 1, deg.
0	6.48	93.24	0	93.24	6.48
15	-12.13	-86.76	0	-93.12	0.114
30	-78.98	74.63	0	86.87	-6.26
45	145.95	-153.61	0	-74.53	12.33
60	-72.66	-60.44	0	153.68	79.14

Table 5: Scan Angles for the Sub-Arrays in the First Stage and for the Array of Sub-Arrays in the Second Stage for Different Overall Scanning Directions

Scanning Angle, deg.	Scanning Angle of Sub-Array 1	Scanning Angle of Sub-Array 2	Scanning Angle of Sub-Array 3	Scanning Angle of Sub-Array 4	Scanning Angle of Sub-Array 5	Scanning Angle of Array of Sub-Arrays
0	30	15	0	-15	-30	0
5	30	15	0	-15	-30	5
10	45	30	15	0	-15	10
15	45	30	15	0	-15	15
20	45	30	15	0	-15	20
25	60	45	30	15	0	25
30	60	45	30	15	0	30
35	60	45	30	15	0	35

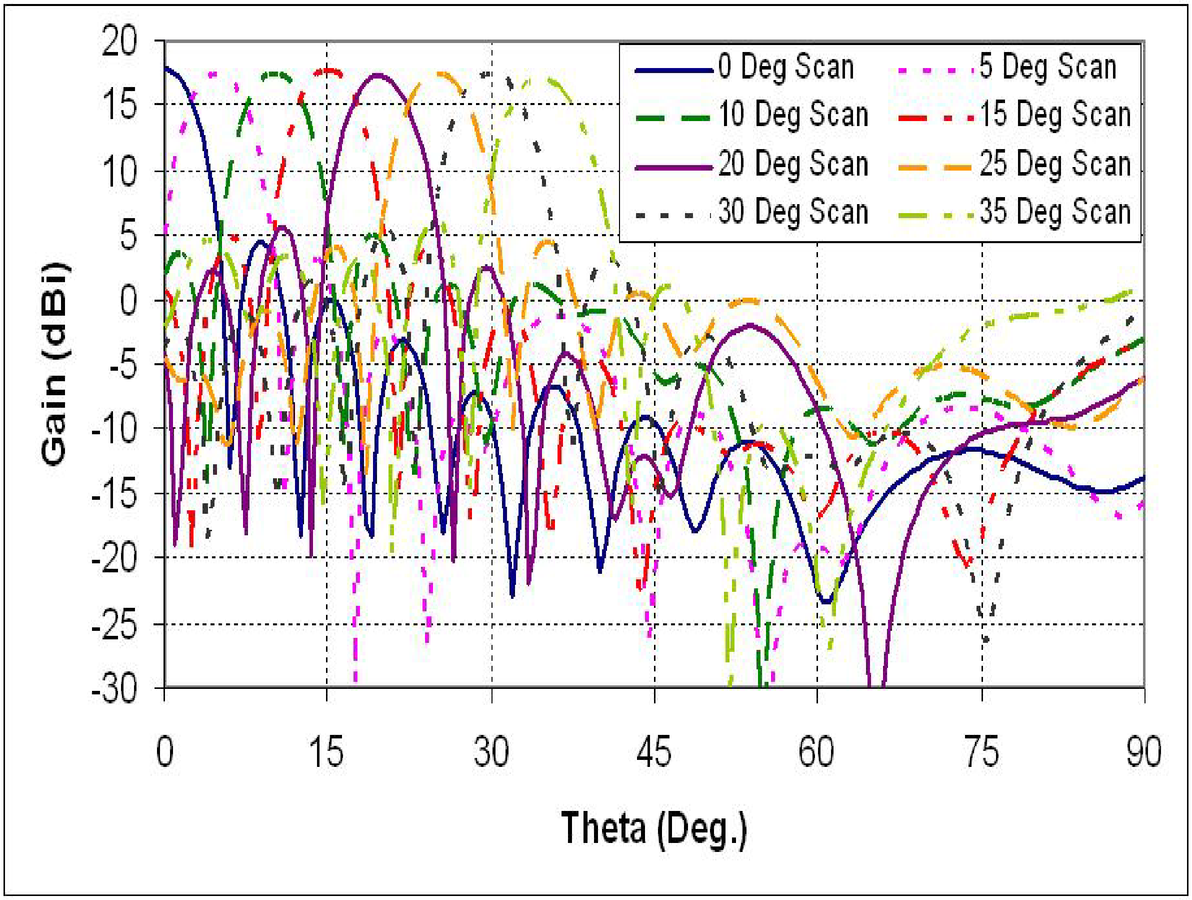

Figure 4. Scanned Patterns for Distributed Beam Forming System

7. CONCLUSIONS

A concept for a distributed beam former was presented in this paper. The concept lends itself to conformal or multi-faceted arrays. The concept has the following features:

1. Two-stage beam forming that will produce scanning directions at small increments over a wide scanning range.

2. Low-loss beam forming, which results from using pre-set fixed scanning directions in the first stage and digital cabling over the longest parts of the signal distribution.

3. Low cost beam forming, which results from using fewer A/D converters and modular sub-array designs.

4. Conformal or multi-faceted array structure that can be stationary or mounted on a HMMWV or other vehicles.

Options for the implementation of the first stage in the beam former were presented. Butler matrix and Rotman lens were discussed. However, other low-loss passive implementations may also be used. The optimization of the beam forming at the two stages is essential for the overall array performance. This includes the pre-set scanning directions in the first stage, which may have significant effects on the RF losses and on the cost of that modular beam former.

The concept was presented for a one-dimensional linear or piecewise linear array and one- dimensional scanning. It can be expanded to planar or piece-wise planar arrays and two-dimensional scanning.

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